Distribution of available Si in soils in relation with land uses types and soil erosion status in West Sumatra-Indonesia

by Hendra Hendra

1. Introduction

Silicon (Si) is an important element for rice production (Imaizumi and Yoshida 1958). However, it is not a concern and has never been applied in sawah in Indonesia. In the field, blast diseases affect local rice varieties, which may be due to the deficiency of available Si, and several studies regarding the Si effect on rice production has been published in Indonesia. Darmawan et al. (2006) reported that about 11%–20% of available Si decreases in sawah soil owing to intensive rice cultivation over the last three decades. In addition, Husnain et al. (2008) reported that in West Java, the supply of Si in lowland sawah through irrigation has decreased because dissolved Si (DSi) is trapped by diatoms (phytoplankton) in dams. However, few studies have focused on the influence of Si availability on rice production and improving Si management.

To mitigate the above problems and thus improve the land-management planning of the watershed, soil erosion must be reduced. To realize this, the present status of soil erosion in relation to land-use pattern in the watershed needs to be evaluated. However, directly determining the soil erosion of the entire watershed is impractical as the necessary measurements are too broad ranging and time consuming. Estimating soil erosion using models is more common and practical. Several types of models for the estimation of soil erosion have been developed, and they include the universal soil-loss equation (USLE; Wischmeier and Smith 1978), WEPP (Amore et al. 2004), ANSWERS (Ahmadi et al. 2006), AGNPS (Walling et al. 2003), and EUROSEM (Morgon et al. 1998). Among these models, process-based ones such as WEPP, ANSWERS, AGNPS, and EUROSEM give logical results. However, they require numerous input data that are generally unavailable and difficult to obtain in most watersheds in Indonesia owing to financial and technical constraints. By contrast, USLE has been used as an evaluation tool for soil conservation throughout Indonesia (Kusumandari et al. 1997; Moehansyah et al. 2004) because it requires a relatively small amount of data and is easy to adopt. The Ministry of Agriculture and Ministry of Forestry in Indonesia has established a standard on soil erosion based on the value estimated by the USLE (Indonesian government role no. 41 in 1999) to control soil erosion. In general, no single best model exists for all applications. Thus, the most appropriate model depends on the purpose of the study and the characteristic of the watershed (Shamshad et al. 2008). In the present study, the application of USLE was evaluated to be sufficient for estimating soil-erosion rates as it can exhibit a relative ranking of soil-loss risk in watersheds when accurate parameter values are used. The

USLE has also been used as a conservation-evaluation tool in Indonesia as aforementioned, although few studies have focused on measuring or estimation soil erosion.

The distribution of silica (silicon dioxide, SiO_2) in soils is influenced by parent material, climate, vegetation, texture, pedogenesis, intensity of weathering (Hallmark & Wilding 1982), and soil-erosion factor. The SiO_2 source for rice plant was derived from soil, irrigation water, and plant residue such as straw and rice husk if they are incorporated into the soil after harvesting. Soils derived from ash volcanic parent material contain more SiO_2 (Imaizumi & Yoshida 1958) than do soils derived from alluvium material, particularly those in lowlands. Many rice fields or sawah located in lowlands has parent materials that are mostly river sediment or alluvium, so the original SiO_2 availability is generally low. Rice is a typical Si-accumulator plant that takes up Si from soil solution through an active mechanism (Ma et al. 2001; Ma et al. 2007).

The present study aimed to determine the factors influencing the distribution of available Si in SW where volcanic ash and Si fertilizer of irrigation water can be natural sources. In sawah soil, pH and total carbon (TC) can be the factors controlling Si availability. Accordingly, we conducted a study on the distribution of available Si in relation to land-use types and soil-erosion status in the SW, a main rice-production area in West Sumatra, Indonesia. We have already previously observed that severe erosion occurred in the highlands of the watershed because of the land-use change from forest to agricultural field. Accordingly, we expected that these factors may influence available-Si distribution in the watershed. Soil erosion is generally regarded as a type of soil degradation. However, it may contribute to nutrient replenishment in sawah, especially in the lowlands, through the deposition of fine soil particles eroded from the highlands, as we discuss in this paper.

2. Material and methods

2.1. Study area and soil sampling

This research was conducted in the SW in the Solok regency of West Sumatra (latitude 00° 36′ 08″ to 10° 44′ 08″ S, longitude 100° 24′ 11″ to 101° 15′ 48″ E). SW has an active volcano, Mount Talang (2500 m asl). Further information about the study area and sample locations are shown in Figs. 1 and 2. On the east side of Mount Talang, we found a lake from which water flows through the lowlands and into lake Singkarak located at an altitude of 300 m asl. All the water of rivers and tributaries that flow into the SW also drain into lake Singkarak. According to data of climatological stations from 1996 to 2000. The SW has a humid tropical climate. The rainfall rate hovers at around 1669 and 3230 mm between altitudes of 300 and 2500 m. Annual temperatures range from 19 °C to 30 °C varying from highlands to lowlands. The average annual humidity also varies from 78.1% to 89.4% (Farida et al. 2005). We selected the SW for our research because of three reasons. First, we already have a database of its soil erosion. Second, the SW has various land-use types (rice fields, forests, mixed garden, garden vegetables, weeds, and bush) suitable for our research (Fig. 2b). Third, this watershed is the central of rice-production area in West Sumatra. Fig. 2a shows the soil sampling in the blue circle. The red circle represents the river-sediment sampling point. We present available Si in soil and collected soil samples from all land-use and soil types and topographical position of the various positions. A total of 23 soil samples were collceted from stream sediments from the highlands to the lowlands. Soil samples were taken at depths of 0–20 cm and 20–40 cm. To view the distribution of soil vertically on highlands and lowland areas, soil samples were taken at a representative area to a depth of 100 cm.

The SW consists of various land-use types, such as primary forest, tree crop garden (mixed garden, coconut, and tea gardens), vegetable garden, sawah, bush (shrub, grass, and alang-alang (land occupied by *Imperata cylindrica*)), and settlement. Sawah means a levelled and bounded rice field with an inlet and outlet for irrigation and drainage (Wakatsuki et al. 1998). Mixed garden refers to land where perennial crops, mostly trees such as coconut, clove, coffee, teak, mahagony, sawo (Achras zapota L), avocado, melinjo (Gnetum gnemon), rubber, and cinnamons, are planted with a combination of annual crops (Karyono 1990). Chili (*Capsicum annum* L.), onion (*Allium cepa* L.), soy bean (*Glycina max* L.), corn (*Zea mays* L.), and sweet potato (*Ipomea batatas* L.) are the major crops in vegetable garden. The watershed is divided into eight geology types, i.e., brecia andesit of Mt. Talang, alluvium of andesit volcano, lava, colluvial deposit, welded tuff, quartz, slate shale part of tuhur form, and lava andesit to basalt (Farida et al. 2005). SW consists of five subwatersheds, namely, Sumani (S1), Lembang (S2), Gawan (S3), Aripan (S4), and Imang (S5).

Located in the SW is the active volcano Mount Talang. Farmers believe that this volcano enriches the soil through its frequent small eruptions and volcanic ash spread on agricultural land throughout the SW. According to Fiantis et al. (2010), the element contents of volcanic ash are SiO_2 (57.61%), Al_2O_3 (16.16%), Fe_2O_3 (5.39%), TiO_2 (0.67%), MnO (0.08%), CaO (4.79%), MgO (1.88%), Na2O (2.51%), K_2O (1.84%), P_2O_5 (0.18%), H_2O^- (1.62%), and H_2O^+ (6.92%).

On 12 April 2005, Mount Talang erupted and ejected ash into the air that then fell and spread throughout the SW. The volcanic ash covered the summit and slopes of Mount Talang with a thickness of 5 and 0.1 cm, respectively, around the foot of Mount Talang. Fiantis et al. (2010) reported that the chemical characteristics of volcanic ash from Mount Talang are as follows: pH H_2O (1:5)(7.26), pH KCl (1:5)(7.12), P Bray 2 (68.02 mg kg^{-1}), P HCl 25% (498.12 mg kg^{-1}), CEC (5.75 cmolc(+) kg^{-1}), Ca (11.14 cmolc(+) kg^{-1}), Mg (2.18 cmolc(+) kg^{-1}), K (0.09 cmolc(+) kg^{-1}), Na (0.12 cmolc(+) kg^{-1}), base saturation (235%), P retention (52.84%), Si in allophone (11.50%), active Al (0.60%), and active Fe (1.99%). Volcanic ash containing 57% SiO_2 is regarded as basaltic andesite. The mineralogy of volcanic ash is dominated by volcanic glass and labradorite.

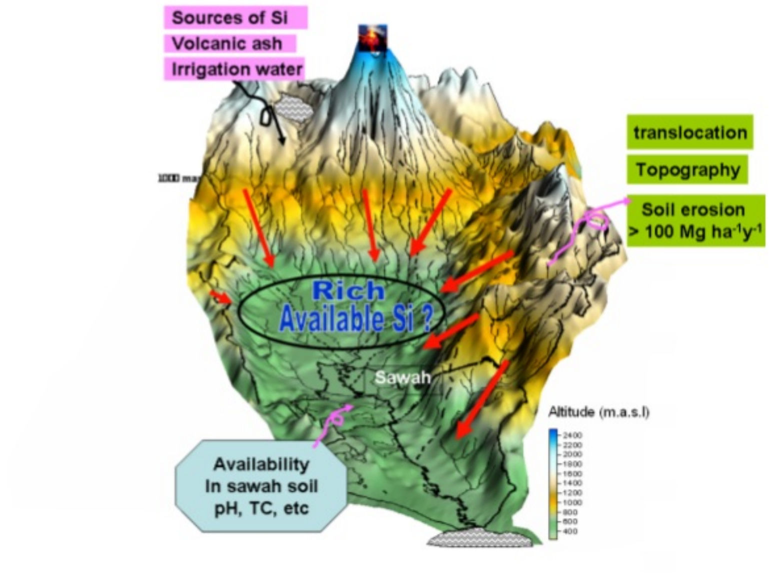

Fig. 1. Possible factors influencing the distribution of Si available in the Sumani watershed.

2.2. *Rice-farming systems*

In the SW, rice is mostly cultivated three times a year as long as irrigation water is available in lowland areas and two times a year in highland areas shifted with vegetables. Irrigation water is usually supplied through irrigation canals and river tributaries. Nitrogen, phosphorus, and potassium are applied in the form of a single nutrient fertilizer (urea, SP-36, and KCl) or compound fertilizer with rates ranging within 46–184 kg N ha^{-1}, 36–72 kg P_2O_5 ha^{-1}, and 6.3–63 kg K_2O ha^{-1} (information from surveyed farmers in study sites). However, KCl is rarely or even not applied in most sawah in the SW because farmers think KCl strengthens only the stall of rice and farmers only need the rice grains. Chemical SiO_2 fertilizer has been never applied to the soil, and SiO_2 has been supplied only from straw returned after harvesting. In terms of straw management in the SW, farmers preferred to burn the straw to shorten the time for the next planting season and thus prevent disease spread in some sites (personal comm. 2009).

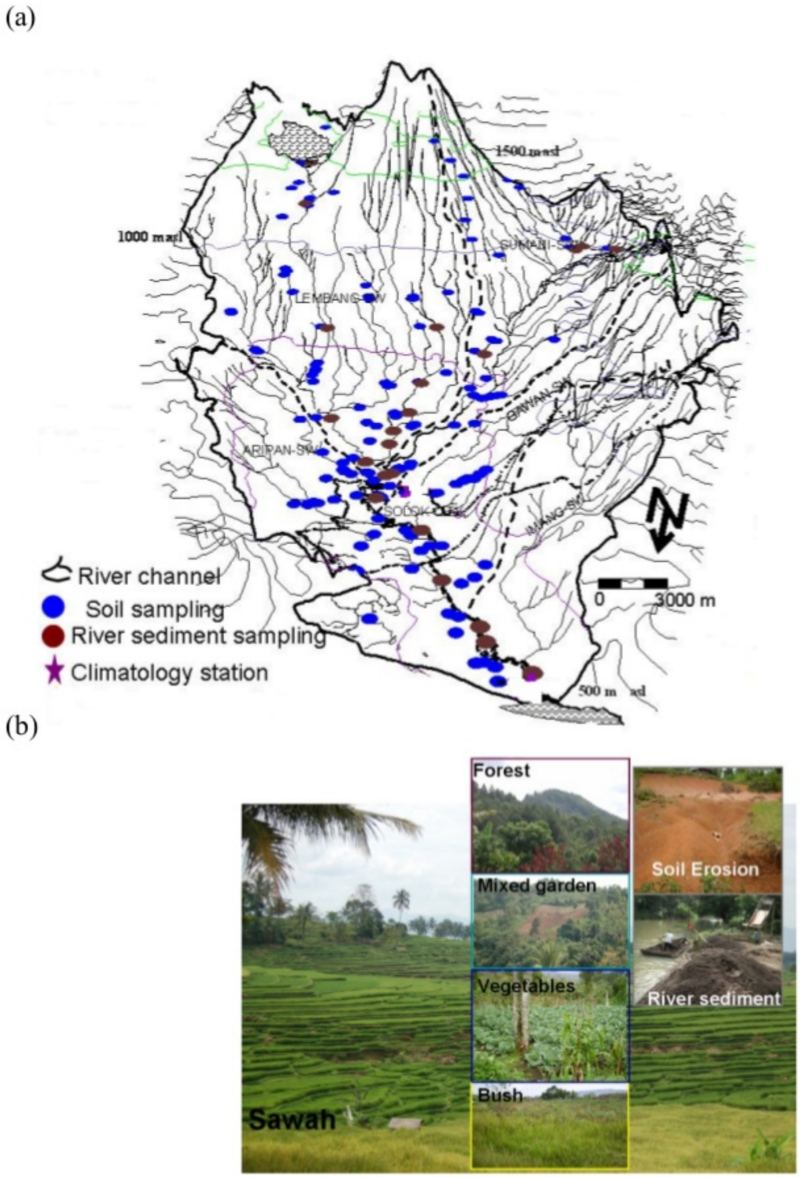

Fig. 2. Sampling point (a) and land-use type (b) in the SW.

2.3. Soil, plant, and water sampling

We collected 143 soil samples based on land-use types and position in the watershed. River sediments were also collected from 23 points to determine available Si. The samples were air dried, ground, and passed through a 2 mm sieve. Plant samples (rice flag leaf) were collected from several sites where soils were sampled. We collected water samples at five points along main rivers and determined the concentration of Si in water every month from August 2006 to February along the SW (Fig. 2) under collaboration with local farmers and staff of Andalas University. A total of 11 water sampling points in the SW were collected from the upper to lower streams of the rivers.

2.4. Soil analyses and estimation of soil-erosion rate

We collected 143 soil samples based on land-use types and position in the watershed. River sediments were also collected from 23 points to determine available Si. The samples were air dried, ground, and passed through a 2 mm sieve. Available Si was extracted using 1 mol L^{-1} acetate buffer (pH 4.0) at a mixing ratio of 1:10 for 5 h at 40 °C with occasional shaking (Imaizumi and Yoshida 1958). Then, the concentration of Si in the filtrate was measured by molybdenum-blue method at 810 nm. Although Sumida (1991) reported that the acetate buffer method is unsuitable for soils previously amended with SiO$_2$ fertilizer, this problem is not found in Indonesia because no silicate fertilizer has been applied (Husnain et al. 2008). TC was determined by the dry combustion method (Nelson and Sommers 1982) using a Yanaco CN Corder Model MT-700 (Yanagimoto MFG. Co., Kyoto, Japan). Soil pH was measured using the glass-electrode method with a soil/water ratio of 1:2.5 (IITA 1979; McLean 1982). Exchangeable base cations (Ca, K, and Na) were extracted using 1 mol L^{-1} neutral ammonium acetate (Thomas 1982), and exchangeable Ca was determined using inductively coupled plasma–atomic emission spectroscopy (Shimadzu ICPS2000, Kyoto, Japan). Exchangeable K and Na were determined using an atomic absorption spectrophotometer (Shimadzu AS 680). Percentage sand and clay were determined by pipette method (Gee and Bauder 1986). Extractable Fe was extracted by 0.1 M HCl and measured with ICP (SSSA 1996). Rice plant was ground into powder, using a tungsten carbide vibrating mixer mill and digested with HNO$_3$ in a high-pressure Teflon vessel (Quaker et al. 1970; Koyama & Sutoh 1987). DSi concentration in water samples was determined with an atomic absorption spectrophotometer (Hitachi Z-5000). Soil-erosion rate in the SW was estimated by USLE (Wischmeier and Smith 1978).

2.5. *Calculation of soil erosion by the USLE model*

We estimated the soil-erosion rate in the SW using USLE (Wischmeier and Smith, 1978), in which annual soil loss is expressed as a function of six erosion factors:

$$E = R \times K \times L \times S \times C \times P \quad (1)$$

where E is the estimated soil loss (Mg ha^{-1}y^{-1}); R is the rainfall erosivity factor (dimensionless); K is the inherent soil erodibility (dimensionless); L is length of the slope factor (dimensionless); S is slope factor (dimensionless); C is the crop cover factor (dimensionless); and P is a factor that accounts for the effects of soil-conservation practices (dimensionless).

The watershed was divided by 39 312 grids with 125 m × 125 m mesh size, and basic data were allocated or estimated in each grid by reading maps and a Landsat image for land-use types and altitude or the kriging method for precipitation and soil properties. Based on these data, respective USLE factors were calculated in each grid unit. To calculate average soil erosion, we excluded the negative value of soil erosion. We used the USLE model because other models require difficult collection of data of detailed rainfall and technical constraint. Detailed calculations of each USLE factor in the SW were have been described by Aflizar et al. (2010).

2.5.1. *Rainfall erosivity factor (R)*

R-factor represents the potential ability of the rain to cause soil erosion. To compute the monthly value of the R-factor, the following equation was proposed for Indonesia by Bols (1998):

$$R = 6.19(Rf)^{1.21}(Rn)^{-0.47}(Rm)^{0.53} \quad (2)$$

where R is monthly erosivity, Rf is total monthly rainfall, Rn is number of rainy days per month, and Rm is the maximum rainfall for a 24 h period in the observed month. Table 1 shows the general monthly rainfall data and monthly values of the R-factor calculated with the above equation for two study periods. No clear dry season appeared in the study area, and the monthly rainfall and R-factor showed no clear seasonal pattern, highly fluctuating year by year.

The R-factor and soil erodibility (K)-factor are generally the most important factors requiring evaluation based on local conditions for the successful application of the model (Chris and Harbor 2002). Not all grids possessed their own data of precipitation or soil analyses to calculate R- and K-factors. In this case, interpolation by the nearest-neighbor kriging method (Golden software 2002) assigned the value of the nearest grid possessing soil-analysis data. This method is useful and yields good results as reported by Goovaerts (2000) and Takata et al. (2008).

2.5.2. *K-factor*

K-factor represents both the susceptibility of soil to erosion and the rate of runoff measured under standard plot conditions. The value for K-factor was computed using the following equation (Wischmeier and Smith 1978):

$$100K= 2.713\ M^{1.14}(10\ -4)\ (12–a)\ +3.25(b-2)\ +2.5(c-3) \quad (3)$$

where M is given by [(St – Svf)/100] – Cf; a is the percentage of soil organic matter content; b is the structural code; c is the permeability class code of the soil; and St, Svf, and Cf are the percentage of silt, very fine sand, and clay fractions, respectively. Details are found in the study of Aflizar et al. (2010)

2.5.3. *Slope length and steepness (LS) factor*

Each grid was considered as a single-slope plane. LS-factor was calculated using the "power form of equation" (Wischmeier and Smith 1978). Liu et al. (2000) reported that the exponent of slope length in the equation does not change with increased slope gradient from 20% to 60%, whereas it changed under the condition of <20%. Thus, two equations were separately used in the present study: Eq. (4) for slope gradient less than 20% and Eq. (5) for slope gradient >20% (Renard and Jeremy, 1994; Irvem et al. 2007).

where L is the slope length (m); S is percentage of slope; X is the slope (degrees); and m is the exponent that varies with the slope gradient, i.e., 0.2 for <1%, 0.3 for 1%–3%, 0.4 for 3.5%–4.5%, and 0.5 for >5%.

2.5.4. *Cover crop (C) and conservation practice (P) factors*

Land-use types in the SW were investigated by interpreting image photos of Landsat TM 2002 confirmed with a field survey in August 2007 and land-use map 1992 based on air photos to have C- and P-factors (Table 1). C- and P-factors were cited from Abdurachman et al. (1984) as these factors are known to insignificantly differ in regions. Different land-use types had respective C-factors. Forest had the smallest and vegetable gardens had the highest C-factor, except for settlement. Major soil conservation practices used in the SW were ground coverage by grass or shrub in vegetable, mixed and coconut gardens, and terrace in Sawah. P-factor is the soil erosion ratio with a specific conservation practice to the corresponding soil erosion with up-and-down slope tillage (Renard et al. 1997). Given that farmers usually perform the same conservation practices for the same land-use type in the SW, P-factor was given to a land-use type following the values suggested by Abdurachman et al. (1984).

2.6. *Data processing for 3D mapping*

Overall data processing involving USLE was conducted using Surfer® 8 (Golden software 2010) dealing with factors gained from a detailed soil survey, digital elevation model, and land-use map. The map of available Si, soil erosion, and land use were computed subsequently using block kriging by taking account of the data within the range.

Block kriging was used instead of punctual kriging because it enables the evaluation of the regional pattern of variation rather than local details owing to the construction of smoother maps with smaller estimation variance (Aflizar et al. 2010). Surfer® 8, produced by Golden Software, Inc. (Golden Colorado), is a relatively inexpensive and user-friendly countering and three-dimensional surface mapping software for scientists and engineers. Basic proficiency with Surfer® 8 can be achieved with a few hours of self-tutoring. Various editions of Surfer® 8 have been applied to the modelling and evaluation of soil heavy-metal contamination and other environmental data (Pazmandi and Tuba 2003). Reported applications typically use Surfer tool as an interface with other software rather than as a stand-alone analytical tool (Aflizar et al. 2010). Surfer software is extensively used but not well documented, with only limited reference to its application to environmental data existing in scientific literature. In the present study, Surfer® 8 was applied as a stand-alone tool to develop a 3D map of soil erosion, available Si, and Land-use pattern distribution from a very large dataset through geostatistical method. In geostatistical methods, the dependence among samples is incorporated into the estimation process

Overall data processing involving USLE was conducted in Surfer® 8 (Golden software 2002) dealing with the factors gained from meteorological stations, detailed soil surveys, topographic maps, and attendant of other applicable studies. The outline of the mapping procedure is explained as follows. To process the mapping of USLE factors described later and the other data, we used regionalized variable theory, which has been successfully applied to soil property interpolation for nearly 30 years. Interpolation is the term a method in Surfer® 8 that uses the optimal delaunay triangulation. The algorithm creates triangles by drawing lines between data points. The original points are connected in such a way that no triangle edges are intersected by other triangles. The result is a patchwork of triangular faces over the extent of the grid. This method is an exact interpolator (Golden software 2002). The theory provides a convenient summary of data variability (in the form of a semi-variogram) and an interpolation technique (i.e., the kriging method). From a theoretical point of view, the kriging method provides the best linear unbiased estimates, an accurate description of the data spatial structure, and valuable information about estimation-error distributions (Kravchenko and Bullock 1999). Individual files for respective parameters of USLE factors and others were constructed by grid-modelling procedures in Surfer® 8 (Golden software 2002) to calculate soil-erosion rate in a spatial domain.

A 1:50 000 topographic map including the SW was inputted into Surfer® 8 by manual digitization. This vector elevation map was converted into grid format with a spatial resolution of 125 m × 125 m. Base on kriging in Surfer® 8, an interpolation routine was used to derive the elevation surface from the rasterized line data. This kriging method and its applicabilities have been described in detail by Takata et al. (2008). The digital elevation map (DEM) was accustomed as the foundation for other topographic-related analyses. The soil properties, land-use types, and other related attributes were also inputted into Surfer® 8 by manual digitization and keyboard entry. Polygons and their attributes were connected with a uniform code. Polygon was the command method used to draw an irregularly shaped area. These vector maps were also converted into raster, which had the same reference system and resolution as the DEM. The data sources were converted into grid format. Each defined grid had an exact location in space determined by the grid orientation and grid size, as well as a list of allocation attributes. To predict soil-erosion rate in the spatial domain, a map unit was set to a size of 125 m × 125 m, which was the finest resolution size suitable for the available data set and authors` computer facilities. Each grid was assumed to be a single slope plane to apply for USLE in grid. The available Si based on the 146 soil-sample coordinates for the entire SW was mapped using kriging in the gridding method in Sufer version 9.

Surfer ® 8 does not contain as a type of spatial structure the relative semi-variogram option, it has only the standardized semi-variogram that is the original semi-variogram rescaled by the lag variance. However, given that a proportional effect existed in the mean and the standard deviation were positively correlated, we used the estimation option proposed. Several models have been fitted to the experimental semi-variogram models. Thus, we performed a cross-validation analysis (Keckler 1994) consisting of the estimation error (Z) at each sample point as if it is unknown, leaving out the observed value at this point. Thus, at every sample point, we obtained an estimated value (Z est), with the true value being the measured value (Z dat). We computed the residual Z res using the following formula:

In this study, we used universal kriging that assumed a constant and unknown mean. As shown in Fig. 1, samples were collected throughout the study area, with the exception of the area at the very steep slope and common land-use forest at the west side of SW because of lack of access to the area. Thus, a polygon with boundaries limiting the area of sampling was used, and estimates were generated only for the area inside it. We used cross-validation to estimate the kriging density through different approaches.

3. Result and discussion

3.1. General soil physicochemical properties

Tables 1 and 2 show general soil physicochemical properties in the SW. The soil had high silt and clay contents and organic matter content of about 5%. Soil permeability and erodibility were high. According to Wischmeier and Smith (1978) and Cassel and Lal (1992), soils with K-factor > 0.04 are generally susceptible to soil erosion. Soil susceptibility to erosion is highly influenced by different climatic, physical, hydrological, chemical, mineralogical, and biological properties (Veihe 2002). Total nitrogen and available Si are low, whereas TC, extractable Fe and Zn are high. Exchangeable base cations (Ca, Mg, K, and Na) were relatively high. Soil physicochemical properties had some correlation with available Si in the SW (Table 2).

Table 1. Available SiO_2 (mg/kg) and erosion-factor analyses in sampling sites in the Sumani watershed

No	Location	Sub waershed	Land use	GPS Reading		R	K	LS	C	P	Erosion Mg/ha/yr	SiO2 (0-20) mg
				East	South							
1	jawi-jawi 1	Sumani	Sawah	681009	9898946	2452,0	0,1	0,0640	0,010	0,4	5,0	204,64
2	jawi-jawi 2	Sumani	Sawah	681007	9898924	2452,0	0,1	0,0640	0,010	0,4	5,0	559,71
3	jawi-jawi 3	Sumani	Sawah	680846	9899016	2452,0	0,1	0,0640	0,010	0,4	10,0	138,86
4	Gantung ciri 1	Sumani	Sawah	679766	9900725	2452,0	0,3	0,0010	0,010	0,4	0,1	258,86
5	Gantung ciri 2	Sumani	Sawah	679906	9900722	2452,0	0,3	0,0010	0,010	0,4	0,1	308,79
6	Gantung ciri 3	Sumani	Sawah	679994	9900676	2452,0	0,30	0,0010	0,010	0,4	5,0	271,93
7	Kelok Duri	Sumani	Sawah	682301	9909213	2452,0	0,10	0,0640	0,010	0,4	2,0	207,86
8	Selayo	Sumani	Sawah	682677	9909496	2452,0	0,10	0,0640	0,010	0,4	2,5	127,07
9	Sawah sudut 1	Sumani	Sawah	682689	9909403	2452,0	0,10	0,0640	0,010	0,4	2,0	201,64
10	Sawah sudut2	Sumani	Sawah	682753	9909451	2452,0	0,10	0,0640	0,010	0,4	2,0	200,79
11	Gawan-sungai 1	Sumani	Sawah	682988	9911695	2452,0	0,30	0,0010	0,010	0,4	15,0	145,50
12	Gawan-sungai 2	Sumani	Sawah	683204	9911613	2452,0	0,30	0,0010	0,010	0,4	10,0	148,29
13	Gawan-sungai 3	Sumani	Sawah	683159	9911560	2452,0	0,30	0,0010	0,010	0,4	15,0	250,71
14	Batu Banyak 1	Lembang	Sawah	690240	9894285	1665,0	0,01	0,6110	0,010	0,4	5,0	157,07
15	Bukik Sileh 2	Lembang	Sawah	690168	9894089	1665,0	0,01	0,6110	0,010	0,4	5,0	168,00
16	Anau kadok 4	Lembang	Sawah	690190	9894077	1665,0	0,01	0,6110	0,010	0,4	5,0	331,07
17	Bukik Sileh 4	Lembang	Sawah	690146	9894586	1665,0	0,01	0,6110	0,010	0,4	7,5	230,14
18	Koto Lawas 1	Lembang	Sawah	690485	9898085	2452,0	0,01	1,7440	0,010	0,4	0,2	148,07
19	Koto Lawas 2	Lembang	Sawah	690385	9898220	2452,0	0,01	1,7440	0,010	0,4	0,2	308,14
20	Koto Lawas 3	Lembang	Sawah	690391	9898224	2452,0	0,01	1,7440	0,010	0,4	10,0	241,71
21	Batu banyak	Lembang	Sawah	689859	9899180	2452,0	0,05	0,0640	0,010	0,4	15,0	203,57
22	Koto Anau	Lembang	Sawah	687948	9902605	2452,0	0,48	0,0640	0,010	0,4	5,0	124,29
23	Sawah Durian 2	Lembang	Sawah	687963	9902709	2452,0	0,48	0,0680	0,010	0,4	5,0	192,64
24	Sawah Durian 3	Lembang	Sawah	688040	9902988	2452,0	0,30	0,0640	0,010	0,4	5,0	165,21
25	Pandan Putih 1	Aripan	Sawah	684981	9909986	2452,0	0,30	0,0640	0,010	0,4	5,0	339,86
26	Pandan Putih 2	Aripan	Sawah	684868	9910153	2452,0	0,30	0,0640	0,010	0,4	5,0	249,64
27	Rawang sari	Aripan	Sawah	684560	9910295	2452,0	0,30	0,0640	0,010	0,4	5,0	427,07
28	Pandan ujung 1	Aripan	Sawah	685806	9912702	2452,0	0,10	0,0010	0,010	0,4	5,0	89,36
29	Pandan ujung 2	Aripan	Sawah	685820	9912612	2452,0	0,10	0,0010	0,010	0,4	5,0	164,79
30	Pandan ujung 3	Aripan	Sawah	685664	9912492	2452,0	0,10	0,0010	0,010	0,4	5,0	192,00
31	Pandan ujung 6	Aripan	Sawah	685437	9912538	2452,0	0,10	0,0010	0,010	0,4	5,0	184,71
32	Parambahan 1	Aripan	Sawah	690900	9902399	2452,0	0,30	0,6110	0,010	0,4	1,8	306,43
33	Parambahan 2	Lembang	Sawah	690786	9902411	2452,0	0,30	0,6110	0,010	0,4	1,8	280,50
34	Parambahan 3	Lembang	Sawah	690734	9902391	2452,0	0,30	0,0640	0,010	0,4	0,2	227,14
35	Sungai janih	Lembang	Sawah	686383	9898559	2452,0	0,05	0,0640	0,010	0,4	15,0	113,36
36	Gunung Talang	Lembang	Sawah	686155	9898931	2452,0	0,05	0,0640	0,010	0,4	10,0	162,64
37	Batu Bajanjang	Lembang	Sawah	686201	9898830	2452,0	0,05	0,0640	0,010	0,4	10,0	120,86
38	Air angek 1	Lembang	Sawah	684168	9898356	2452,0	0,30	0,0640	0,010	0,4	5,0	500,57
39	Anau Kadok 2	Lembang	Sawah	684089	9898413	2452,0	0,30	0,0640	0,010	0,4	5,0	139,50
40	Anau Kadok 3	Lembang	Sawah	684138	9898260	2452,0	0,30	0,0640	0,010	0,4	10,0	243,21
41	Pasar usang	Lembang	Sawah	684550	9903109	2452,0	0,30	0,0640	0,010	0,4	5,0	374,57
42	Panyalaian Cupak	Lembang	Sawah	684404	9903287	2452,0	0,30	0,0640	0,010	0,4	0,2	364,71
43	Kubu	Gawan	Mixed Garden	679336	9910716	2452,0	0,30	2,5120	0,200	0,5	640,0	534,86
44	Parak gadang	Gawan	Mixed Garden	680767	9911154	2452,0	0,30	0,0640	0,200	0,5	45,0	445,29
45	Gunung Talang	Sumani	Mixed Garden	681796	9902683	2452,0	0,10	0,0640	0,200	0,5	30,0	476,79
46	Gantung Ciri	Sumani	Mixed Garden	679878	9903305	2452,0	0,20	0,0640	0,200	0,5	5,0	211,71
47	Curang gadang sasak	Sumani	Sawah	677000	9902000	2452,0	0,09	2,5120	0,010	0,4	115,0	262,29
48	Kayu aro	Sumani	Tea	680022	9890308	1665,0	0,07	0,0640	0,001	1,0	20,0	326,79
49	Pasar usang guguk	Lembang	Mixed Garden	682500	9898000	2452,0	6,10	0,0640	0,200	0,5	45,0	679,07
50	Koto baru	Lembang	Sawah	683508	9905910	2452,0	0,20	0,0640	0,010	0,4	3,0	508,07
51	Lembang	Aripan	Bush	681302	9914208	2452,0	0,20	0,0010	0,950	0,4	1,0	543,00
52	Jawi-jawi	Sumani	Mixed Garden	679878	9903305	2452,0	0,20	0,0640	0,200	0,5	5,0	955,71
53	Sukarami BPTP	Sumani	Bush	680390	9895606	1665,0	0,10	0,0640	0,290	1,0	15,0	447,86
54	Danau kambar	Sumani	Tea	680586	9890624	1665,0	0,07	0,0640	0,001	1,0	15,0	217,93
55	Air batumbuk	Lembang	Bush	685164	9886435	1665,0	0,20	0,0640	0,290	1,0	85,0	260,79
56	Bungo tanjung	Lembang	Mixed Garden	693126	9883658	1665,0	0,10	1,7440	0,200	0,5	5,0	382,71
57	Air tawar	Lembang	Mixed Garden	691000	9887152	1665,0	0,10	2,5120	0,200	0,5	30,0	497,79
58	Bukik sileh	Lembang	Sawah	688906	9894277	1665,0	0,00	2,1380	0,010	0,4	5,0	509,14
59	Koto anau	Lembang	Sawah	687977	9902100	2452,0	0,20	0,0010	0,010	0,4	5,0	245,79
60	Air Mati	Aripan	Bush	684848	9912166	2452,0	0,30	2,1380	0,950	0,4	1,0	616,29
61	Bukik gompong	Sumani	Mixed Garden	681722	9895558	1665,0	0,10	2,1380	0,200	0,5	85,0	576,64
62	Kampung jawa 1	Sumani	Mixed Garden	682165	9894832	1665,0	0,10	2,1380	0,200	0,5	65,0	857,14
63	Kampung jawa 2	Sumani	Mixed Garden	682148	9894165	1665,0	0,02	3,6130	0,200	0,5	10,0	227,36
64	Tower TVRI 2	Sumani	Forest	682440	9893752	1665,0	0,02	2,8770	0,001	1,0	40,0	316,50
65	Tower bukik gompong	Sumani	Forest	683120	9893547	1665,0	0,06	2,8770	0,001	1,0	5,0	358,29
66	Laing 1	Aripan	Grass	680718	9915222	2452,0	0,10	0,0010	0,290	1,0	2,5	89,36

67	Laing 2	Aripan	Forest	685090	9917469	2452,0	0,48	2,1380	0,001	1,0	3,5	560,79
68	Laing 3	Aripan	Grass	685251	9917230	2452,0	0,48	2,1380	0,290	1,0	285,0	243,86
69	Laing 4	Aripan	Mixed Garden	685283	9917147	2452,0	0,48	2,1380	0,200	0,5	270,0	98,57
70	Saok laweh	Aripan	Sawah	686353	9912829	2452,0	0,10	0,0010	0,010	0,4	5,0	261,00
71	Ganangan	Lembang	Mixed Garden	684733	9906341	2452,0	0,20	0,0640	0,200	0,5	10,0	437,36
72	Balai pinang	Lembang	Sawah	685276	9905296	2452,0	0,30	0,0640	0,010	0,4	0,2	289,29
73	Guguk rantau	Lembang	Bush	682703	9906436	2452,0	0,20	0,0640	0,290	1,0	5,0	372,00
74	Koto baru	Lembang	Forest	682595	9906283	2452,0	0,20	0,0010	0,001	1,0	5,0	791,14
75	Sawah suduk	Sumani	Bush	682276	9908944	2452,0	0,10	0,0640	0,290	1,0	5,0	313,29
76	Pakan senayan	Sumani	Mixed Garden	680780	9906663	2452,0	0,10	0,0640	0,200	0,5	1,6	201,21
77	Selayo	Gawan	Sawah	679843	9907068	2452,0	0,30	0,0640	0,010	0,4	5,0	264,43
78	Durian X koto	Gawan	Forest	680026	9914546	2452,0	0,10	0,0010	0,001	1,0	0,0	153,64
79	Koto sani	Imang	Bush	678451	9916455	2452,0	0,30	0,0010	0,290	1,0	0,2	309,00
80	Aie angek	Imang	Mixed Garden	678169	9915663	2452,0	0,20	2,5120	0,200	0,5	123,2	355,71
81	Sumani 1	Imang	Sawah	677426	9921191	1288,0	0,10	0,0010	0,010	0,4	5,0	292,50
82	Panyalaian Cupak	Lembang	Sawah	684275	9903267	2452,0	0,30	0,0640	0,010	0,4	5,0	299,36
83	Sumani 2	Aripan	Sawah	677681	9921448	1288,0	0,10	0,0010	0,010	0,4	5,0	128,36
84	Aur Duri	Imang	Sawah	678648	9919152	1288,0	0,10	0,0640	0,010	0,4	25,0	392,14
85	Belimbing	Imang	Sawah	678905	9916775	2452,0	0,30	0,0010	0,010	0,4	3,0	313,50
86	Durian	Aripan	Sawah	680453	9914773	2452,0	0,10	0,0010	0,010	0,4	4,0	295,93
87	Sawah Parit	Aripan	Sawah	685480	9910916	2452,0	0,30	0,0640	0,010	0,4	10,0	182,36
88	Guguk Dama	Aripan	Sawah	685080	9909609	2452,0	0,30	0,0640	0,010	0,4	5,0	228,64
89	Batu Juriang	Aripan	Sawah	686098	9908995	2452,0	0,20	0,064	0,010	0,4	10,0	288,86
90	Muaro Paneh	Aripan	Sawah	687639	9906755	2452,0	0,20	0,064	0,010	0,4	4,0	120,64
91	Koto Gadang Koto An	Lembang	Sawah	687895	9903389	2452,0	0,30	0,064	0,010	0,4	5,0	200,57
92	Koto Anau	Lembang	Sawah	688034	9902271	2452,0	0,20	0,064	0,010	0,4	5,0	235,93
93	Koto Laweh	Lembang	Sawah	690464	9898410	1665,0	0,01	1,744	0,010	0,4	3,0	200,79
94	Bukit Sileh	Lembang	Sawah	691249	9895502	1665,0	0,10	0,064	0,010	0,4	20,0	196,70
95	Bukit Sileh 2	Lembang	Vegetable	691275	9895481	1665,0	0,10	0,064	0,400	0,5	20,0	203,79
96	Kampung Batu	Lembang	Sawah	691024	9893027	1665,0	0,10	0,064	0,010	0,4	5,0	310,29
97	Kampung Batu 2	Lembang	Vegetable	691156	9891364	1665,0	0,10	0,064	0,400	0,5	50,0	102,43
98	Dilam 1	Lembang	Sawah	692432	9900886	1665,0	0,30	3,399	0,010	0,4	10,0	157,50
99	Dilam 2	Lembang	Sawah	692462	9900828	1665,0	0,30	3,399	0,010	0,4	10,0	152,79
100	Dilam 3	Lembang	Sawah	692483	9900815	1665,0	0,30	3,399	0,010	0,4	10,0	189,43
101	Sumani 3	Aripan	Mixed Garden	677030	9921312	1288,0	0,10	0,001	0,010	0,4	0,0	412,07
102	Aripan 1	Aripan	Mixed Garden	676813	9922182	1288,0	0,10	0,001	0,200	0,5	0,0	355,29
103	Aripan 2	Aripan	Mixed Garden	678613	9919968	1288,0	0,10	0,064	0,200	0,5	1,0	1115,36
104	Aripan Pompa	Aripan	Mixed Garden	679004	9919123	1288,0	0,10	0,064	0,200	0,5	1,0	756,43
105	Tanjung Bingkung	Aripan	Mixed Garden	680785	9916791	2452,0	0,30	0,611	0,200	0,5	56,0	427,93
106	Bbanda pandan	Aripan	Mixed Garden	681581	9913781	2452,0	0,20	0,001	0,200	0,5	1,0	633,00
107	Kota Solok	Aripan	Mixed Garden	684026	9911713	2452,0	0,30	0,064	0,010	0,4	1,0	634,50
108	Batu kualo	Lembang	Mixed Garden	684727	9909217	2452,0	0,20	0,064	0,200	0,5	5,0	296,36
109	Muaro paneh	Lembang	Mixed Garden	686990	9906478	2452,0	0,20	0,064	0,200	0,5	5,0	200,79
110	Lembang atas	Lembang	Mixed Garden	688122	9900659	2452,0	0,05	0,611	0,200	0,5	28,0	391,50
111	Bukik sileh	Lembang	Mixed Garden	690986	9894498	1665,0	0,20	3,400	0,200	0,5	200,0	389,79
112	Batu banyak	Lembang	Mixed Garden	691380	9891131	1665,0	0,10	0,611	0,200	0,5	14,0	794,14
113	Kubung	Lembang	Mixed Garden	684313	9907711	2452,0	0,20	0,064	0,200	0,5	5,0	166,93
114	Bukik kili 1	Lembang	Mixed Garden	684276	9906492	2452,0	0,20	0,064	0,200	0,5	5,0	375,00
115	Bukik Kili 2	Lembang	Mixed Garden	683659	9905507	2452,0	0,30	0,064	0,200	0,5	0,0	329,14
116	Cupak sungai	Lembang	Mixed Garden	683030	9903030	2452,0	0,30	0,064	0,200	0,5	5,0	308,57
117	Talang	Lembang	Mixed Garden	683500	9900067	2452,0	0,20	0,064	0,200	0,5	5,0	334,71
118	Lubuk silasih	Sumani	Mixed Garden	677332	9893200	1665,0	0,05	1,740	0,200	0,5	56,0	216,21
119	Lubuk silasih 2	Sumani	Mixed Garden	677090	9893546	1665,0	0,05	0,610	0,200	0,5	5,0	391,07
120	Lubuk selasih 3	Sumani	Forest	675194	9893700	1665,0	0,05	0,001	0,200	0,5	1,0	106,29
121	Kapalo banda	Sumani	Mixed Garden	680662	9901560	2452	0,30	0,001	0,01	0,4	0,0	289,29
122	Kota Solok 2	Lembang	Mixed Garden	683872	9910003	2452	0,30	0,064	0,20	0,5	5,0	229,07
123	Kota Solok 3	Lembang	Mixed Garden	683981	9909967	2452	0,30	0,001	0,20	0,5	1,0	343,29
124	Aripan 3	Aripan	Mixed Garden	681485	9920988	1288	0,09	0,001	0,20	0,5	1,0	101,57
125	Kubung 1	*Sumani*	*Sawah*	*683541*	*9910512*	2452	0,30	0,001	0,01	0,4	1,0	209,57
126	Kubung 2	*Sumani*	*Sawah*	*682817*	*9910806*	2452	0,30	0,064	0,01	0,4	1,0	179,14
127	Batu palano	Gawan	sawah	680861	9911165	2452	0,30	0,064	0,20	0,5	5,0	220,07
128	Ketaping 1	Gawan	Sawah	680081	9910640	2452	0,30	0,611	0,01	0,4	1,0	201,86
129	Ketaping 2	Gawan	Mixed Garden	679815	9910540	2452	0,30	0,611	0,20	0,5	100,0	282,86
130	Ketaping 3	Gawan	Sawah	679659	9910488	2452	0,30	0,611	0,01	0,4	1,0	220,07
131	Ketaping 4	Gawan	Mixed Garden	679437	9910599	2452	0,30	0,064	0,20	0,5	5,0	137,57
132	Gawan 1	Gawan	Forest	679098	9910622	2452	0,30	2,510	0,00	1,0	1,0	136,29
133	Bukit kili 1	Gawan	Forest	678850	9910573	2452	0,09	2,510	0,00	1,0	1,0	130,29
134	Bukit Kili 2	Gawan	Sawah	682115	9911144	2452	0,30	0,064	0,01	0,4	1,0	255,86
135	Aripan 4	*Aripan*	*Sawah*	*682803*	*9913171*	2452	0,20	0,001	0,01	0,4	5,0	127,29
136	Aripan 5	*Aripan*	Mixed Garden	*682701*	*9914550*	2452	0,20	0,001	0,20	0,5	0,0	150,21
137	Destamar 1	*Aripan*	Mixed Garden	*682863*	*9916064*	2452	0,10	0,001	0,20	0,5	0,0	94,07
138	Destamar 2	*Aripan*	Mixed Garden	682652	9917803	2452	0,40	0,064	0,20	0,5	100,0	113,36
139	Destamar 3	*Aripan*	Mixed Garden	682652	9917803	2452	0,40	2,140	0,20	0,5	100,0	263,57
140	Gantung Ciri 1	Sumani	Sawah	680501	9903987	2452	0,10	0,064	0,01	0,4	1,0	309,86
141	Gantng Ciri 2	Sumani	*Sawah*	*679916*	*9904572*	2452	0,20	0,001	0,01	0,4	1,0	292,00
142	Puluan 1	Sumani	Mixed Garden	679772	9904605	2452	0,20	0,064	0,20	0,5	1,0	421,93
143	Puluan 2	Sumani	Sawah	679503	9904591	2452	0,20	0,064	0,01	0,4	1,0	313,50
144	Puluan 3	Sumani	Mixed Garden	*679278*	*9904592*	2452	0,20	0,611	0,20	0,4	14,0	194,36
145	Bukik Singo-singo	Sumani	Mixed Garden	679032	9904638	2452	0,20	0,611	0,40	0,5	56,0	178,71
146	Bukik Singo-singo 2	Sumani	Mixed Garden	*680264*	*9904469*	2452	0,20	0,611	0,01	0,4	28,0	274,07
					Mean							299,80
					Median							259,83
					Max							1115,36
					Min							89,36
					SD							177,21

Table 2. General soil physicochemical properties in the Sumani watershed

	Mean	(Range)	SD	r^a
Sand (%)	9.0	(0.4-58.0)	11	0.08
Very fine sand (%)	2.0	(0.4-9.0)	2	0.01
Silt (%)	55.0	(0.0-85.0)	20	0.02
Clay (%)	33.0	(9.0-95.0)	20	-0.05
Organic matter (g kg^{-1})	54.0	(21.0-111.0)	24	0.01
Soil permeability (cm h^{-1})	93.0	(0.0-1506.0)	286	0.01
Soil erodibility (K)	0.22	(0.0-0.5)	0.1	0.17*
Bulk density (g cm^{-3})	0.9	(0.5-1.3)	0.2	0.01
Soil pH H2O 1:2.5	5.5	(4.2-7.2)	0.5	0.32**
Total Carbon (g kg^{-1})	34.6	(7.2-151.4)	27.6	0.01
Total Nitrogen (g kg^{-1})	3	(0.4-9)	0.17	0.01
Exchangeable Ca (cmolc(+) kg^{-1})	10.6	(0.023-29.7)	6.1	0.45**
Exchangeable K (cmolc(+) kg^{-1})	0.4	(0.1-1.9)	0.4	0.38**
Exchangeable Na (cmolc(+) kg^{-1})	0.9	(0.002-3.7)	0.7	-0.28**
Extractable Fe (mg kg^{-1})	204.2	(0.02-1500.6)	289	-0.17*
Available Si 0-20 cm (mg SiO2 kg^{-1})	300.0	(89.4-1115.4)	177	

3.2. Available Si and other general soil properties

Table 3 shows the mean soil properties of the land-use types. According to Bollich and Matichenkov (2002) and Sumida (1992), available Si levels less than 600 and 300 mg $SiO_2 kg^{-1}$ are considered to be “low” and “deficient” for rice plant growth. Based on these criteria, most of the sites were grouped into the categories of “low” and “deficient,” indicating that soil in the SW was generally low in available Si. This finding may explain the blast diseases frequently observed in this watershed. Tea plantation showed a high TC, and vegetable garden showed a low pH. In the SW, the low Si availability may be associated with the intensive agricultural practices and the absence of additional Si fertilizer by farmers, in addition to the high rainfall that transports Si from the surface soil through erosion and runoff. This region has the annual contribution of volcanic ash from Mt.Talang to the agricultural area on the island of Java as mentioned by Kawaguchi and Kyuma (1977). However, the high activities of rice farming and vegetable and tea planting have resulted in the mining and transport of Si through the process of harvesting (Darmawan et al. 2006).

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Table 3. Mean of available Si and other general soil properties in the SW

	pH	TC	Availa-ble Si	Exchang-eable Ca	Exchange-able Na	Exchang-eable K	Extracta-ble Fe
		(g kg^{-1})	(mg SiO2 kg^{-1})		(cmolc kg^{-1})		(mg kg^{-1})
Sawah (n=78)	5.5	34.6	262.4	9.88	1.14	0.26	298
Mixed garden (n=48)	5.6	45.2	375.9	13.89	0.31	0.72	114
Vegetables (n=2)	4.6	26.7	153.1	7.32	0.29	1.28	104
Tea (n=2)	5.3	123.9	272.4	6.07	0.25	0.22	16.3
Forest (n=8)	5.8	57.3	319.5	13.24	0.38	0.31	19.2
Bush (n=7)	5.6	38.2	290.9	10.57	0.40	0.30	18.7
River Sediment (n=23)	5.5	34.6	393.7 262.4	9.88	1.14	0.26	298
Criteria of available Si level in sawah soil							
Deficiency level*				300.0			
Low level**				600.0			

*Matichenkov (2002)

** Sumida (1992)

Table 4 shows the average Si available in soil at 0–20 cm depth in the SW and 5 subwatershed (S1, S2, S3, S4, and S5). The Si concentration was lower than that in the Citarum watershed, Kaligarang Watershed on Java Island, and Seedfarm and Non-Seedfarm sawah on Java Island. This finding may be due to the different numbers of growing seasons of sawah and the soil geology. The intensive rice cultivation has led to Si mining and exportation through harvesting processes (Darmawan et al. 2006). Differences in the parent material also appeared to be the major factor influencing Si in soils at the watershed scale (Darmawan et al. 2006; Husnain et al. 2008).

Table 4. Average available Si in 0–20 cm soil depth of some selected sawah in the SW and other watersheds in Indonesia

Location		Area (km^2)	n soil sample	Available Si in Soil (0-20 cm) depth (mg SiO_2 kg^{-1})
Sumani subwatershed (S1)	Sumatera Island	176.70	19	241.63
Lembang subwatershed (S2)	Sumatera Island	191.80	34	261.01
Gawan subwatershed (S3)	Sumatera Island	80.40	6	219.32
Aripan subwatershed (S4)	Sumatera Island	70.40	16	210.57
Imang subwatershed (S5)	Sumatera Island	64.00	3	332.71
Sumani Watershed (SW)	Sumatera Island	583.3	78	253.05
Citarum Watershed[a]	Java Island	6949	6	504.83
Kaligarang Watershed[a]	Java Island	210	6	460.33
Sededfarm [b]	Java Island		18	1283.00
Non-Sededfarm [b]	Java Island		22	1202.00
Sededfarm lowland[b]	Java Island		12	1804.00
Sededfarm upland[b]	Java Island		6	1005.00
Non-Sededfarm lowland[b]	Java Island		13	1187.00
Non-Sededfarm upland[b]	Java Island		6	1226.00

3.3. Relationships between soil chemical properties and availability of SiO_2 in the SW.

pH showed a positive relationship with the availability of Si, i.e., Si availability increased with increased pH the. This phenomenon may be due to the high availability of Si in high-pH soil possibly because of the influence of volcanic ash from Mount Talang. According to Fiantis et al. (2010), Mount Talang volcanic ash contains CaO (4.79%), exchangeable Ca (cmol 11:14 (+) kg^{-1}), and pH H_2O 1:5 (7:26).

Volcanic ash very rapidly decays and releases nutrients compared with primary minerals. The weathering process of volcanic ash releases Ca and other elements, including available Si and K as indicated by an increase in pH (Fig. 3). Ca, K, and Si from volcanic ash are released into the soil, where the nutrients become available to the plants through the process of exchange with free hydrogen protons in the soil.

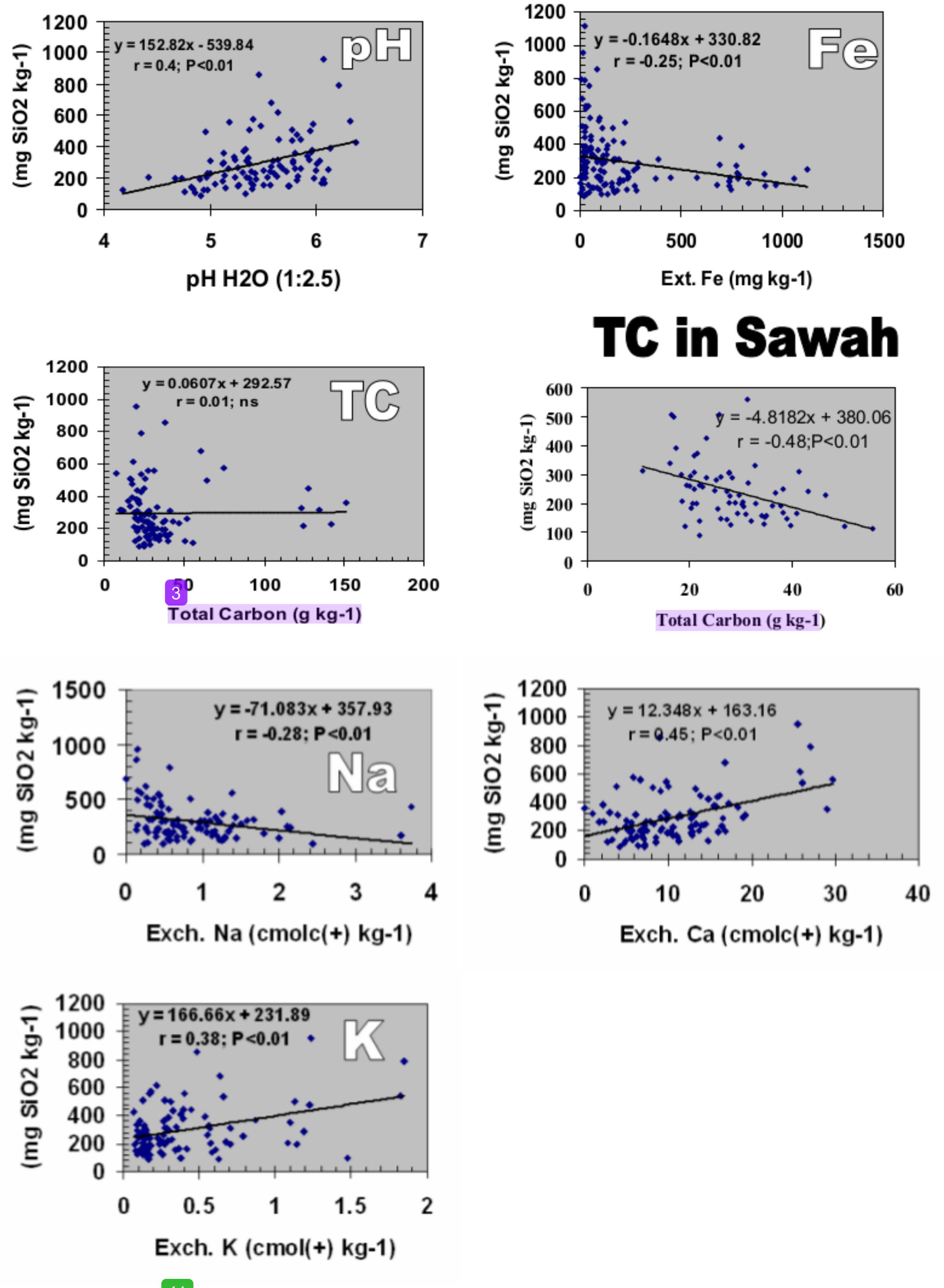

Fig. 3. Relationship between available Si and soil chemical properties of soils.

Conversely, the concentration of hydrogen protons from soil decreased with increased concentrations of Ca, K, and available Si, resulting in increased pH. This process may have occurred throughout the entire SW. To enable the process of release of nutrients needed by plants from volcanic ash, sourcing a substantial amount of hydrogen protons is necessary. In the SW can originate from inorganic acids released from the eruption of Mount Talang which always occurs in small and medium scale in the past until now. In addition, organic acids derived from the exudates of biota can be a source of hydrogen protons (Fiantis et al. 2010; Dahlgreen et al. 1999). The weathering of volcanic ash occurs through surface exchange with aqueous hydrogen ions (Shoji et al. 1993). The main sources of protons for the weathering of volcanic ash include acidic aerosols, carbonic and organic acids. Acidic aerosols comprise sulphuric acid (H_2SO_4), hydrochloric acid (HCl), fluoric acid (HF), and nitric acid (HNO_3), which originate from the eruption plume, whereas carbonic and organic acids originate from biota (Dahlgren et al. 1999). Besides an increase in the concentration of silicon in the soil because it deals with pH, Ca and K. extractable Fe and Exchangeable Na is the opposite effect, namely reducing the availability of Si concentration in the soil. The highly extractable Fe showed a negative correlation with Si availability. This finding may have been due to the indirect effect of soil pH, where Fe solubility was high at low pH and the low pH was related to the solubility of Ca, K, and Si. Jansen et al. (2003) reported that the solubility of Fe (III) was higher at pH 4 and 5. Conversely, the solubility of Fe (II) and Al was high at pH 3.5.

Exchangeable Na led to increased concentrations and thus to the low availability of Si. This finding was most likely due to the Na in the form of sodium carbonate (Na_2CO_3) reacting with SiO_2 and the liquid form of sodium silicate (Na_2SiO_3) and CO_2 (Greenwood et al, 1997). We suspected that Na_2SiO_3 was a form of Si unavailable to plants. Si is available for plants in the form of Si (OH_4) (Saccone et al. 2009), H_4SiO_4 (Tian et al. 2008). The solubility of Si in soil solution ranged from pH 2 to 9, and Si typically comes in the form of orthosilikat. We speculated that Na_2CO_3 formed from the reaction of Na ions with carbonate ions. According Bischoft and Rosenbaver (1996), CO_2 reacts with water to form H_2CO_3 at low temperatures. H_2CO_3 then dissociates to form H^+ and HCO_3^-. Highlands in the SW has a minimum temperature of <19 °C that enables the formation of Na_2SiO_3. $Na_2SiO_3$is characterized by very low ionization constants and can thus form hydrous Na_2SiO_3 sediment in various forms depending on the Na concentration (Sebag et al. 2001).

Regarding TC, we found no significant correlation for all land-use types. However, when we extracted sawah soil, a negative correlation was found between TC and Si availability. This finding was due to the high TC in sawah soil because of the high rice production. Darmawan et al. (2006) reported that the TC of sawah soil has increased by 13.7% during the 30 years of intensive cultivation of rice in Java, Indonesia. The high production of rice meant that Si was highly consumed. They changed from Si in a form available for plants to be biogenic Si in the form of Si which is not available for plants. Si in the remaining plants so that decomposes organic material is a form of Si which is generally in the form of biogenic Si, which in form is not available as plants (Imaizumi and Yoshida 1958). Changes in the form of available Si as biogenic Si may explain why soil with high TC had decreased available Si. Darmawan et al. (2006) reported that intensive rice without Si fertilizer and mining Si has resulted in the soil through the process of harvesting. Thus, the availability of Si in sawah in Java soil decreased by 11%–21% within 30 years.

3.4. Soil-erosion map and distribution of Si availability

The soil-erosion map in the SW in 3D is presented in Fig. 4. The average rate of erosion in the SW was 58.91 Mg ha^{-1}y^{-1}. However, soil erosion was much greater than the average erosion in the highlands where the lands sloped. In the hilly area adjacent to Mount Talang (highland areas S1 and S2), soil erosion ranged within 100–200 Mg ha^{-1}y^{-1}. Meanwhile, in the hilly area that lies on the west side (upper position of S2, S3 and S5), soil erosion exceeded 200 Mg ha^{-1}y^{-1}. Conversely, in the lowlands (particularly S1, S2, S3, S4, and S5) soil erosion was very low. According to Aflizar et al. (2010), the highest soil erosion occurs in hilly areas in the SW highlands caused by land-use change from forest to agriculture and by natural factors such as erodibility added soil and high rainfall. Meanwhile, soil erosion in the lowlands was low because a sawah generally had a band to prevent erosion. The average annual erosion in the SW is 58.91 Mg ha^{-1}y^{-1}, which has produced as much sediment in the SW is 6.18 Mg ha^{-1}y^{-1}with an average of SDR is 10.5%. This finding indicated the accumulation of eroded soil particles in the flat bottom of the watershed area where the land is sawah. The 3D soil-erosion map in the SW is shown in Fig. 4.

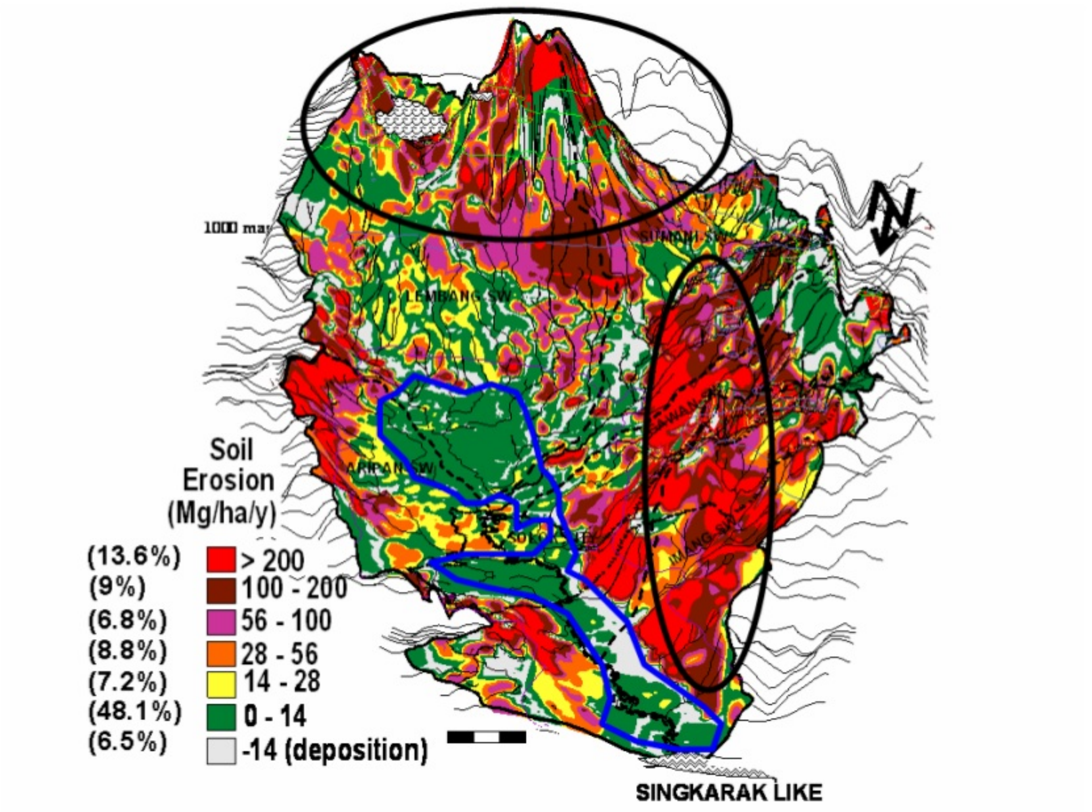

Fig. 4. 3D soil-erosion map in the Sumani watershed.

Fig. 5 shows the 3D distribution of Si availability in the SW. In the highlands S1 and S2 (located near Mount Talang), Si availability was relatively higher than those in the western side of the SW, which includes the areas on the upper positions (S1, S3, and S5). We compared Figs. 3 with 4 and found high soil erosion on both sides. However, in the hilly area near the Mount Talang (the highlands Si and S2), Si availability was relatively higher those in the west areas. This finding may be due to the fact that the area around Mount Talang received fresh volcanic ash from its eruption, and the surrounding soil type is andisol derived from basalt andesite. Fiantis et al. (2010) reported that the eruption of Mount Talang on April 12, 2005 belched 5 cm-thick volcanic ash into the air before falling over the surrounding areas.

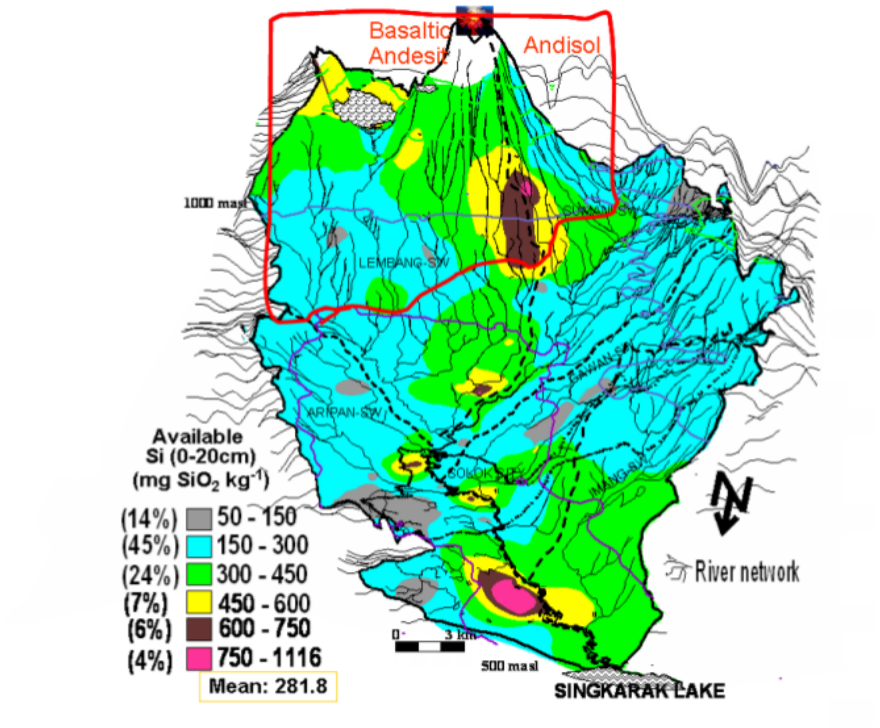

Fig. 5. Distribution of available Si in soil.

Volcanic ash contains approximately 57.61% SiO_2, and the main mineral is volcanic glass and labradorite. Qafoku et al. (2004) reported that volcanic glass is more brittle and elements are more easily released to the soil solution compared with primary minerals.

For the hilly areas far from Mount Talang, Figs. 4 and 5 illustrate high soil erosion with low content of Si (upper positions of S2, S3, S4, and S5) and low erosion with relatively high availability of Si (lowlands S1, S2, S3, S4, and S5). Vegetable land mostly had low Si availability (Table 2 and Fig. 3), where the show is located at the highest regional rate of erosions. Severe soil erosion can carry away available Si on the soil surface. Conversely, the availability of Si was relatively high at sawah and generally distributed in the lowlands (Figs. 3 and 4), where most sediment accumulation occurs (Fig. 3). Aflizar et al. (2010) reported the results of the estimation method for the location kringing deposition of eroded in sawah. They found numerous eroded soil particles on the topography of the watershed that were transported and accumulated at sawah in the lowlands. At lowland soil layers deeper than the Upland area. We believe that this finding may be due to the accumulation of particles eroded from highlands in the lowlands. Local farmers also believe that the lowlands originated from the eroded soil of the highlands (Personal communication, 2009). Lowland areas of geology data showed that soil derived from basaltic andesite colluvial deposit from Mount Talang in the highlands was transported in large quantities through soil erosion a hundred years ago.

Fig. 6 shows the vertical distribution of Si availability in the highlands and lowlands. We found lower availability of Si on the soil surface than in the subsoil because more Si was consumed by plants or leached into the subsoil. This result also indicated the influence of soil erosion on the distribution of Si. To examine the effect between the Si consumption by plants or Si loss by soil erosion, we attempted a simple calculation and found that the total annual production of vegetable crops, mixed gardens, and rice in the SW was 27 Gg y^{-1}, whereas the total erosion and total river sediment each year were 3436 Ggy^{-1} and 360 Ggy^{-1}, respectively. The average Si in rice leaves in java was 120 350 mg SiO_2kg^{-1} (Husnain et al. 2008), and Si in the soil in the SW was 300 mg $SiO2kg^{-1}$. Thus, the SiO_2 lost each year through plant consumption was 3252 Mg y^{-1}, whereas the SiO_2 lost through soil erosion was 1031 Mg y^{-1}. Thus, these data illustrated that erosion greatly influenced soil Si loss, and we expected to lose ground in SiO_2 from the watershed scale, we expect the transfer layer of topsoil is eroded by erosion. Consistent with the increased erosion every year owing to changes in land use (Aflizar et al. 2010), the loss of SiO_2 in the watershed scale continued to increase every year.

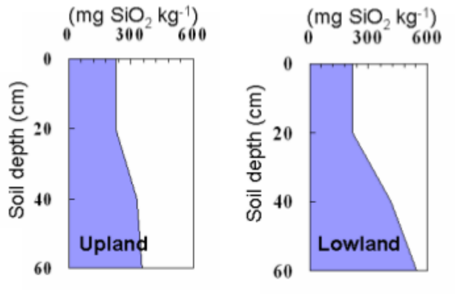

Fig. 6. Vertical distribution of available Si.

Fig. 7 explains the direction of material movement due to soil erosion in the watershed, where the direction of movement Sumani material is indicated by blue arrows. The arrow was made based on altitude and slope degree in the SW simulation by using a vector in Surfer ® 9. The material apparently moved from highlands S1 and S2 and then accumulated sediment in the lowland S2. Material from the upper position while S2, S3. S4 and S5 collected in lowland S3, S4, and S5. Benefits received by the lowland area is the discovery of the availability of high Si at lower positions. This fact, probably due to the transport surface soils containing high SiO_2 through soil erosion. We also suspected that erosion increased the content of Si in river water and irrigation because the soil contained particles in the form of sediment. We subsequently observed SiO_2 in river and irrigation water.

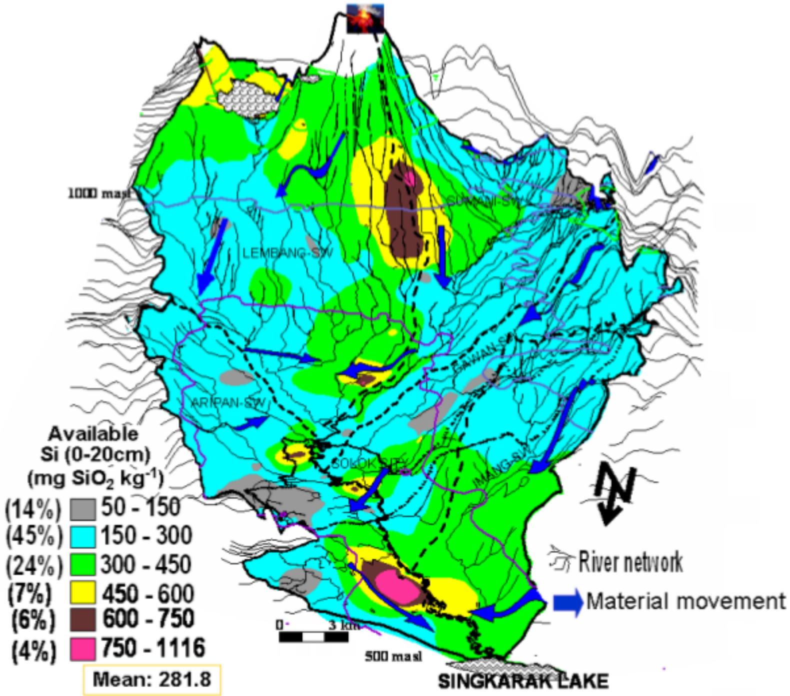

Fig. 7. Direction of material movement in the Sumani watershed.

3.5. Concentration of DSi in river water and irrigation

High soil erosion in highland watershed and the effect on the increase of sediment in river water and irrigation. This phenomenon can affect the DSi concentration in river water and irrigation (Fig. 8). DSi in rivers and irrigation water on average ranged from 5–54 mg kg^{-1} SiO_2 in the interval of observation from August 2006 until February 2007. DSi was higher in the lowlands than in the SW highlands. In the SW, DSi concentrations in water were higher than those in the DSi in the Citarum watershed, Indonesia (12.6–36.6 mg SiO_2 kg^{-1}) (Husnain et al. 2006). DSi in the second watershed was generally low because no SiO_2 fertilizer was present in the SW. Thus, DSi from rivers and irrigation water can be a source of SiO_2 fertilizer. As reported by Imaizumi and Yoshida (1958), the 30% SiO_2 sources for rice is derived from river water and irrigation water. Fiantis et al. (2010) performed laboratory experiments and found that phosphorus and other elements including Si in volcanic ash of Mount Talang are leached out within 3000 days through water as leaching agent and within less than 2000 days by using organic acids (citrate and oxalic acid). In summary, available-Si distribution was influenced by various factors, as shown in Fig. 9.

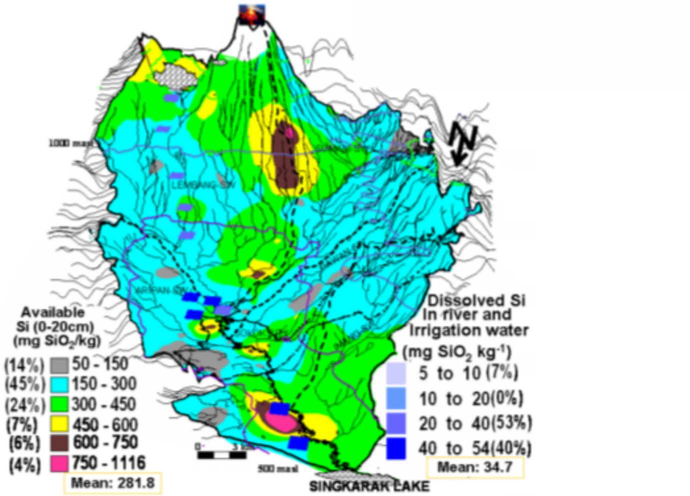

Fig. 8. Dissolved Si in river and irrigation water in the Sumani watershed.

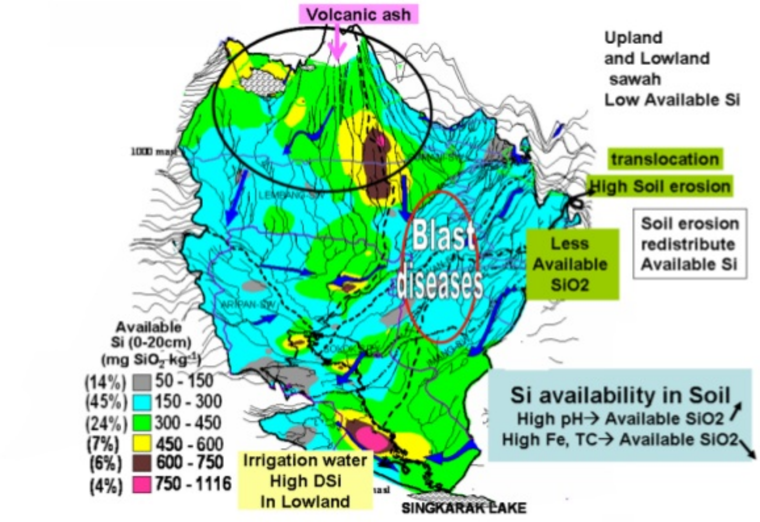

Fig. 9. Diagram of available-Si distribution influenced by various factors.

Table 5 shows that the average Si concentration in the river at SW was greater than those in the rivers in the Citarum and Kaligarang watersheds, as well as other asian countries (Thailand, Malaysia, Sri Lanka, and Japan). The average Si in irrigation water in the SW was also greater than that in Java Island and irrigation water in Japan. This finding may be due to the fact that SW has a natural Si source in the highlands of Mount Talang, which greatly contributes Si to springs and rivers and irrigation. High Si concentrations in river water and irrigation in the SW are the largest contributors of Si to sawah as a counterweight to Si in the soil. The contribution of natural SiO_2 resources as irrigation water reportedly play important roles in maintaining the available-Si concentration in soil (Darmawan et al. 2006). Kawaguchi and Kawaguchi and Kyuma (1977) found moderate Si concentration in river water, which are the dominant sources of irrigation in Java Island, Indonesia.

Table 5. Average Si concentration (mg SiO_2 L^{-1}) in irrigation and river water from Sumani Watershed, Java Island, and other Asian countries

Location		Area (km^2)	SiO_2 concentration (mg SiO_2 L^{-1})
Irrigation water in Sumani Watershed (SW)	Sumatera Island, Indonesia	583.3	32.65
River water in Sumani Watershed (SW)	Sumatera Island, Indonesia	583.3	40.94
Lake Dibawah in Sumani Watershed	Sumatera Island, Indonesia		5.96
Irrigation water in Java [1]	Java Island, Indonesia		14.00
River water in Java [2]	Java Island, Indonesia		29.82
River water Citarum Watershed[3]	Java Island, Indonesia	6949	24.05
River water Kaligarang Watershed[3]	Java Island, Indonesia	210	37.28
River water in Thailand[2]	Thailand		17.19
River water in West Malaysia[2]	Malaysia		13.01
River water in Sri Lanka[2]	Sri Lanka		13.07
River water in Japan[2]	Japan		19.00
Irrigation water in Japan[4]	Japan		10.20

[1] Darmawan et al.2006 ;[2]Kawaguchi and Kyuma. 1977; [3] Husnain et al.2008; [4]Kumagai et al. 2002

3.6. Cross-validation of field measurements

Before using a simulation map and optimizing a mathematical model, the accuracy of the simulation map or the model with the original data should be verified (Theodossiou et al. 2006). The verification is not intended to prove the model accuracy but to ensure the absence of systematic errors, which play important roles in bias estimation (Kitanidis 1983).

The verification procedures were implemented as follows. The concentration of available Si from 146 soil-sample points were analysed in the laboratory through the same methods and equipment. With the help of kriging method in Surfer ® 8, the estimated distribution map of available Si was created. Then matched back with the result of analysis of available Si in the laboratory. The differences between the results of analyses available Si in the laboratory and the estimated values were recorded.

The distribution map is considered unbiased in the sense that if the basic assumptions made were true, then the difference between the analyses of available Si map would be zero. In any other case, the estimated value would be conditionally biased. An example of this is found in the greater estimation value or smaller value measured in laboratory. Fig. 10 shows the correlation of the concentration of available Si measured with the estimation map of available Si. The result can easily be observed that the available Si was distributed around a straight line at 45°. This finding showed that the estimation map of available Si was unbiased. The isolated points were located below 45°, indicating that the estimated value was incorrect or soil samples in locations required more soil samples. This fact explains the observation on that area needs to be a lot of soil sample, especially in the area have different in geology, land use and topography.

Theodossiou et al. (2006) reported when using kriging, the occurrence of a large difference between the laboratory and estimated values should not depend on the actual value but only on the location of soil sample, which was representative area that can be simulated (or not) by measuring the actual value. Fig. 11 shows the distribution diagram of the correlation between the estimation error (the difference between available Si and estimated value) and estimates of available Si. Again, this can be seen easily that the value is distributed around the horizontal straight line which demonstrates that the estimated error value is almost zero. The estimated value of the large error did not depend on the actual estimated values.

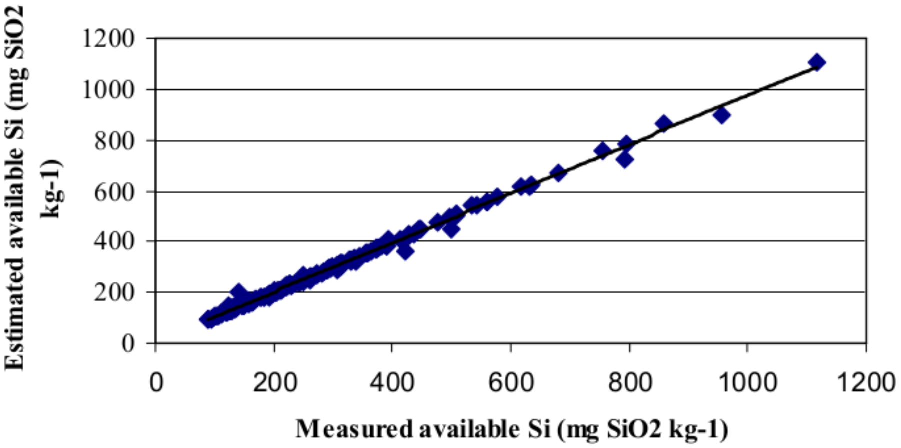

Fig. 10. Correlation between measured available Si in the laboratory and estimated value.

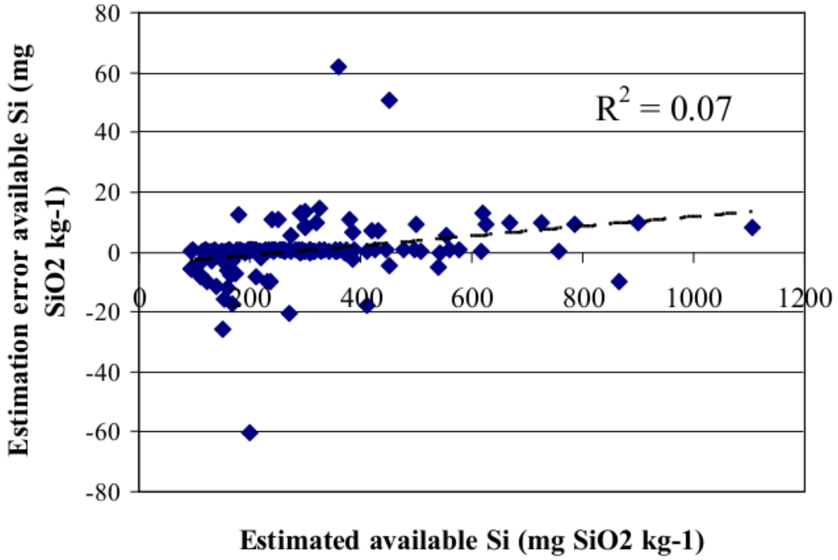

Fig. 11. Correlation between the estimated available Si and estimated error.

4. Conclusions

Volcanic ash and Si from irrigation was a major source of Si in the SW. Soil erosion transported soil surface rich in SiO_2, making it available to lowlands. Meanwhile, the river water in the surrounding highlands had high erosion and low SiO_2 availability. Low pH, high extractable Fe, and high exchangeable Na showed relatively low availability of SiO_2. Given these factors, the availability of Si distribution in the SW. When Si availability in soil was low, we found rice blast disease. Generally, Si availability in the SW was low. However, in areas close to Mount Talang, is the height of the addition of SiO_2 from volcanic ash, also in the lowland areas through irrigation water. However, on the west side of the SW, the area we found the availability of SiO_2 sawah low especially at high topography on the west side of the SW, which is now found in many diseases according to the results of interviews with farmers. Blast disease occurred based on our observations but not in the area surrounding Mount Talang. This finding may be due to the contribution of SiO_2 from volcanic ash Mount Talang. For the sake of a sustainable management of watershed, we recommend the addition of SiO_2 to rice fields. Possible sources of SiO_2 include coal fly ash because it is so widely available in Indonesia.

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